tempting) to suspect the principle of detailed balance, especially in view of the recent suggestion[11] of the possibility of a strong violation of C and T invariance in the electromagnetic interaction of strongly interacting particles. We believe, however, that a great deal of careful work remains to be done before other explanations of the discrepancy can be rigorously excluded.

A more detailed account of this work will be published later, together with an analysis of the pion-nucleon s-wave scattering amplitudes.

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PROTON COMPTON SCATTERING MEASUREMENT FROM 450 TO 1350 MeV NEAR 90° IN THE CENTER-OF-MASS SYSTEM*†

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We have performed an experiment to measure the 90° c.m. differential cross section for γ,p scattering (proton Compton scattering), for incident laboratory photon energies (k_L) between 450 and 1350 MeV. It is our ultimate goal to obtain enough information in the form of angular distributions to contribute to the understanding of resonances. Our present data, at a single angle, are not of great value for that purpose, although we do see the effects of the first, second, and third π,p resonances, and possibly a higher one. It remains to be seen whether our data agree with theoretical predictions. In the region of the first resonance, previous experimental results[1] agree well with a dispersion-theory treatment.[2] One feature of this process which simplifies the analysis is the smallness of the elastic cross section in comparison with the various inelastic pion-photoproduction cross sections. The effect of this is that the reactive effect of the elastic-scattering process on itself, through the unitarity condition, is negligible. At the same time, the reactive effects of the inelastic channels are not only important but are, in principle, known in terms of measured processes. This situation prevails throughout the region of our data.

Our apparatus is shown in Fig. 1. The recoil proton is detected in the scintillation counters $S2$, $S3$, and $S4$ with its track being recorded in the thin spark chambers $SC3$, $SC4$, and $SC5$. The scattered photon is converted with 0.7 probability in the lead spark chamber $SC1$ (1.96 radiation lengths), and counted in the scintillator $S1$ and in the 2-in. lead glass Cherenkov counter C; the shower development is observed in the lead chamber $SC2$ (4 radiation

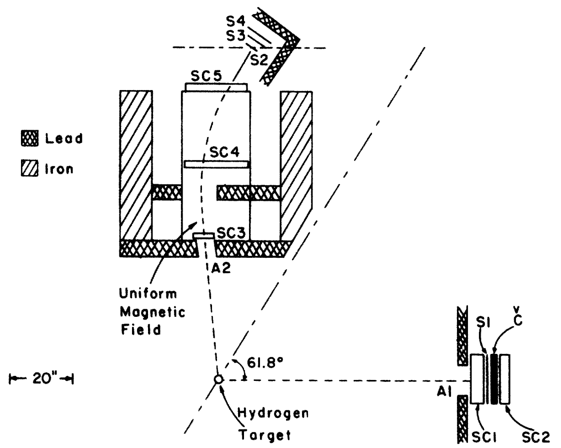

FIG. 1. Experimental equipment.

lengths).

The key requirement for this experiment is the precision of measurement to permit use of the two-body kinematics for discriminating from π^0 photoproduction. We measure the proton momenta to about $\pm 1\%$, and we extrapolate our proton tracks back to the target to a precision of about $\pm\frac{1}{8}$ in. For each event we calculate from the proton angle and momentum the predicted γ position assuming it to be a Compton event. There are then vertical and horizontal discrepancies between the measured and predicted γ positions. We separate our data, on the basis of vertical discrepancy, into a band containing the Comptons (approximately coplanar) and the rest. We then plot the horizontal discrepancies as shown in Fig. 2. The noncoplanar events are normalized on the tails, as shown, to give a simulated background curve. The background events consist mainly of single π^0 photoproduction with less than 10% being double pion production. Of course, the charged pions could have been rejected on the basis of their tracks in the γ chamber, but in most cases we have not bothered.

About 95% of the Compton events are contained between the arrows in Fig. 2. We say that these events are in the "Compton rectangle." Before dividing by the calculated efficiency to get cross sections we must subtract the background. We assume that for the background the distribution in k_L is the same inside and outside the Compton rectangle. This is a good approximation, since γ rays from π^0 decays illuminate the chamber fairly uniformly. At worst this introduces a systematic error which varies slowly with k_L. With this assumption

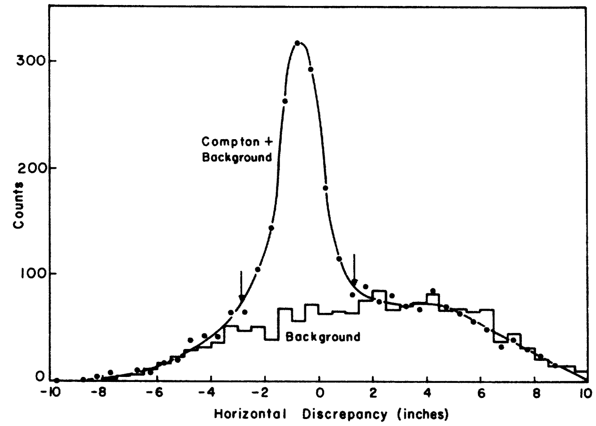

FIG. 2. Plot showing Compton-to-background situation. The horizontal discrepancy plotted is the difference between predicted and measured positions of the scattered photon. The events plotted have already been selected to be approximately coplanar.

we have good statistics on our background, and our statistical error is dominated by fluctuations in our background plus foreground counts in the Compton rectangle. We normalize our background distribution (as a function of k_L) to give the ratio of areas (background over Compton plus background) indicated by Fig. 2. Our present data consist of three such sets.

We took 30 000 pictures of which about one in eight is a Compton event. Most of the film was measured by an automatic scanner.[3] The first half of the γ-ray pictures were measured by hand for want of a computer program to reconstruct the showers. Also, scattered samples of both proton and γ-ray pictures were scanned by hand, either because imperfections on the film prevented automatic scanning or to check the automatic scanner. Except that the machine scanning was slightly more accurate and reproducible, there was good agreement. Some 10% of the γ-ray pictures were uninterpretable either by hand or by machine. Some 20% of the proton pictures were uninterpretable by machine scan (largly due to lack of programming sophistication), although less than 5% were uninterpretable on hand scanning.

Apart from picture inefficiencies there were various other corrections: γ-ray geometric inefficiency (~5%), γ-ray conversion inefficiency (30%), Comptons outside Compton rectangle (~5%), empty target (<1%) and accidentals (~5%). Having corrected for these effects, we expect less than 10% systematic error and negligible energy-dependent error.

Our magnet aperture was determined from the measured magnetic field by calculating limiting trajectories. Since our three proton spark chambers were all in regions of almost uniform field, the fringe field is unimportant in determining the proton momenta. The fringe field is important in the determination of the proton angles. Its effect was checked by extrapolating the trajectories back to the target plane and comparing with the known target position. Systematically this comparison disagreed by about 1 in. and we corrected accordingly, assuming the fringe-field measurement to be incorrect. This had no significant effect on our results. We were also able to check our aperture calculations qualitatively by comparing expected and observed distributions of proton angle and momentum. This was conveniently done by making a dot plot of proton angle against proton momentum. Events on this plot fall in a banana-shaped region. (Protons with high momentum and small angle or low momentum and large angle were simultaneously detected.) The boundaries of this region can be compared with the theoretical boundaries. Of course, the dots on this plot have a diffuse boundary, but within that limitation the comparison was satisfactory. Plots of horizontal and vertical distributions of events in the target plane were made. The distributions reproduce the actual target distributions rather well since our measurement errors were small compared to the target region (which was $1\frac{1}{4}$ in. long and $\frac{1}{2}$ in. high). A final over-all check on the precision utilizes the two-body kinematics of the Compton events themselves. Lack of precision contributes to the width of the Compton peak as plotted in Fig. 2. The dominant source of this width was multiple scattering in the hydrogen target. Error in localization of the γ ray contributes negligibly to this width while inaccuracies in proton determination begin to be significant at the highest momenta.

For each of our three sets of data the magnet angle, proton defining aperture, counter $S2$, and magnetic field were adjusted to have the following desirable property. At each proton angle there is a range of proton momenta acceptable by the magnet system and, in particular, a central momentum. Correspondingly, there is a central elastic γ-ray angle in the lab. The magnet aperture was arranged so that this γ-ray angle was essentially constant independent of incident photon energy. This was possible even though a range of several hundred MeV was detected simultaneously. The value of this compensation was in permitting a small γ-ray aperture (5 in. $\times$ 10 in. at a distance of 80 in.), and consequently a small

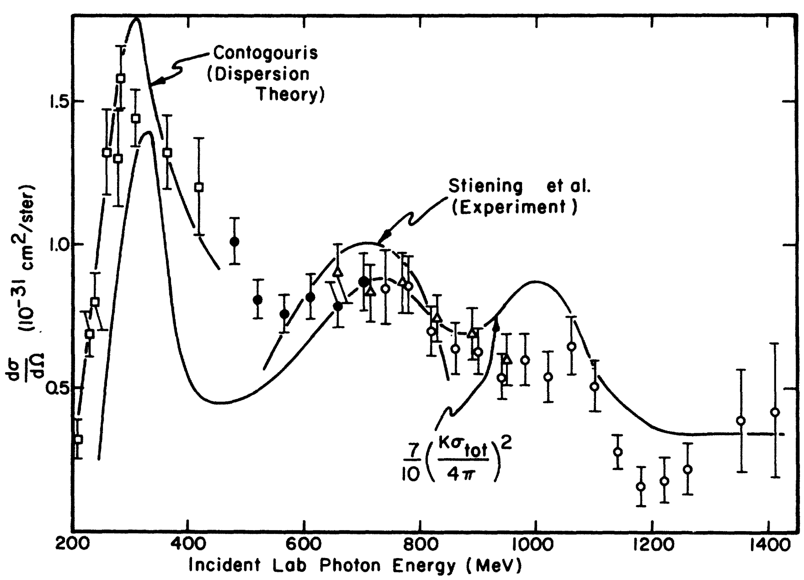

FIG. 3. Measured differential cross sections. The open squares are previous measurements.[2,5] The rest of the points are new with the different symbols indicating different independent series of data. Nominally, all points are at 90° in the c.m. Actually the c.m. angle of the photon is 80° at $k_L = 450$ MeV and 100° at 1350 MeV and varies approximately linearly in between.

π^0 detection efficiency, with no expense in Compton efficiency.

Our results are shown in Fig. 3. Also shown are earlier results[2,4] at lower energies and results of Stiening, Loh, and Deutsch[5] which are represented by a smooth curve through their data.

There seems to be considerable promise for computing Compton scattering in this region in terms of measured photoproduction cross sections.[3,6] A simple model assumes that at the energies in question, all absorption takes place from the $J=\frac{3}{2}$, $M1$ channel (first resonance) or the $J=\frac{3}{2}$, $E1$ channel (second resonance). Above 500 MeV there is significant π^- pair production, which we also assume comes from the same two channels. This would be true if, for example, pion pairs were predominantely formed by the decay of the second resonance into the first resonance and a pion. In the absence of experimental information we ignore charge combinations other than π^+, π^-. Both of the above channels lead to an angular distribution $3\cos^2\theta+7$ in Compton scattering. We assume the scattering to be completely absorptive and temporarily we ignore interference between the two contributions. Using the optical theorem to get the elastic cross section at 0° from the total photoproduction cross section (σ_{tot}), we then obtain the 90° cross section by the formula

$$\frac{d\sigma}{d\Omega}(90°)=\frac{7}{10}\left(\frac{k\sigma_{\text{tot}}}{4\pi}\right)^2, \tag{1}$$

where k is the c.m. incident photon energy. This prediction is shown in Fig. 3.[7] This model is very similar to one of Minami.[6] The discrepancy between 400 and 600 MeV could be due to the interference of real parts which we have neglected. The interference contributes to the angular distribution a $\cos\theta$ term which vanishes at 90°, but affects our model through its effect on the 0° cross section. We plan to investigate this further by measuring forward and backward cross sections.

While this model is very crude, it does give a fairly good qualitative description of the data. The important feature is the k^2 dependence in Eq. (1). This factor has the effect of enhancing higher resonances compared to lower ones. Minami predicted this effect for the second resonance and this was borne out by the work of Stiening, Loh, and Deutsch,[5] and by this experiment. Our measurements in the region of the third resonance were undertaken to find if the third resonance is enhanced in the same way. This appears to be the case. Of course, there is no reason to suppose that the factor of 7/10 is appropriate at this energy.

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